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Relocation of naturally-spawned salmonid ova as a countermeaure to patchiness in adult distribution at spawning

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and
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Introduction

It has been known for many years that, before they spawn, salmonids home to the rivers where they lived as juveniles. More recently, it has been recognised that for many returning fish homing is very precise, indeed. Tagging studies carried out at the Girnock Burn fish-trap on the Aberdeenshire Dee have shown that, on average, slightly more than half the adult Atlantic salmon caught entering the stream to spawn have been tagged there previously, leaving the stream as smolts (Youngson *et al.*, 1994). The source of the untagged fish which enter the stream is not known. However, it is likely that many of the untagged fish have also originated in or near the Girnock Burn because the trap in which the smolts are caught for tagging is located several hundred metres from the stream's confluence with the main stem of the river Dee. Indeed, the proportion of untagged fish caught at the Girnock trap can be accounted for solely on the basis of estimates of smolt production in the stretch of stream between the trap and the river.

The Girnock Burn is a small tributary to a large river. The main stem of the River Dee is about 126 km in length and the river's total catchment area is about 2,100 km^2. The Girnock Burn drains a minor sub-catchment of about 28 km^2. The stream's confluence with the main river is 85 km distant from the sea. On their return from the sea, homing salmon must pass upstream through a large part of the complex of water courses that drains the lower part of the river's catchment in order to reach the Girnock Burn. They must also refuse potential opportunities for spawning in the upper reaches of the river catchment, by leaving the main river stem in order to target the tributary. About 10 km of the Girnock Burn's length is accessible to spawners and those of the Girnock Burn smolts that return as adults to the stream must therefore home with a precision that is equal to, or less than, this distance.

These observations are evidence that the recruitment of adult salmon to spawning populations depends, to a substantial extent, on the return of smolts that have left the same vicinity in previous years. Extending the argument, the relatively fine geographical scales appropriate for considering juvenile populations and adult spawning populations must also apply to consideration of the abundance of adult salmon in the fisheries, since recruitment to the fisheries is driven by homing fish. Thus, any local weakness in spawning populations, that results in locally reduced densities of fry and parr and in sub-maximal smolt production, is expected to result later on in a shortfall in the fisheries.

In addition, some of the seasonal characteristics of the fisheries are determined by the special characteristics of particular populations. For example, salmon returning to populations in different reaches of single river catchments contribute in different ways to the same river's various seasonal runs. In general, early-running fish among both grilse and 2SW-salmon tend to belong to upper river catchments (Laughton and Smith, 1992); late-running fish tend to spawn lower down (Smith *et al.*, 1998). In these circumstances, weaknesses in particular spawning populations will be reflected in shortfalls in particular seasonal components of the fishery.

Variation in migratory behaviour may be attributable to genetic differences among populations. Since homing is precise, genetic exchange among salmonid populations in different rivers and in different parts of the same river is constrained. This has resulted in the development of genetic population structuring within Scottish rivers (Jordan *et al.*, 1992; 1997; Thompson, 1995). It is likely that fish belonging to particular populations are better-adapted for life in their own locations than in others (Verspoor and Jordan, 1989; Jordan *et al.*, 1990, 1998; Jordan and Youngson, 1991) and probably, therefore, better-adapted to their own locations than fish brought in from elsewhere (Taylor, 1991; National Academy of Sciences, 1996).

In recent years, increasing concern has been expressed about declines in Scottish fisheries for both salmon and sea-trout as a result *inter alia* of reduced levels of marine survival (Shelton *et al.*, in press). In response, various initiatives have been

considered with a view to ensuring that the number of juvenile salmonids leaving rivers is maintained at high levels. Enhancement work based on hatchery effort in its various forms, ranging from the planting out of unfed fry to releasing captively-reared smolts, is often advocated. At first sight, the use of such methods appears to be an attractive option that offers rapid and large-scale solutions to all salmonid fishery problems.

The conventional remedy for sub-optimal patterns of spawning and uneven habitat uptake by juveniles is to intercept adult spawners and to redistribute their progeny to streams by way of hatcheries, usually by planting out fry. Hatchery management has been practised widely in this way for many years. More recently, the development of aquaculture-based techniques for enhancement has increased the range of options available to managers which now extends to include the development of fisheries based to a large extent on the release of reared smolts (Ritter, 1997).

It is now widely recognised that all hatchery work is constrained by the importance of local population structuring among wild salmonids, since it suggests that hatchery broodstock, and the progeny they generate for planting, should be matched with appropriate streams (Buggert, 1998). Additionally, the viability of stocked fish may be reduced by inappropriate hatchery environments (Ewing and Ewing, 1995) or mismatches between hatchery and stream environments in the period before release (Hansen and Jonsson, 1989; Staurnes *et al.*, 1993). Certainly the return rates of reared smolts are almost invariably lower than those of wild ones (Jonsson *et al.*, 1991). In many circumstances, the relatively low return rates obtained from reared fish (see eg Whelan, 1993; Russell, 1994: McDermott *et al.*, 1996) and the high capital and labour costs involved in setting up and running centralised hatcheries combine to make the cost of each adult return to the fishery appear high.

As a consequence of these types of effect, the validity of some hatchery programmes has been questioned (Bowles, 1995) and some forms of hatchery-driven management have been criticised (see eg White, 1995). Under these circumstances, the development of novel, low-intervention methods offers an alternative approach that incorporates an appropriate local component to enhancement (Davidson and Bielak, 1993). In North America, for example, an approach has been developed that is based on highly devolved, so-called 'satellite' hatchery and rearing systems. Such arrangements have been used to tap voluntary effort at a local level and to stimulate the involvement of local communities in biological conservation (Sherer, 1990). In this paper we consider another locally-based approach to increasing the production of salmonids. The approach has been devised to increase the utilisation of suitable habitat by emergent fry and to reduce density-dependent mortality during early stream-life.

The locations in which adult fish spawn are determined, to a large extent, by the sedimentary and flow characteristics of streams. The distribution of spawning-calibre gravel in salmonid streams is non-uniform along their length (Moir *et al.*, 1988). The uptake of potential spawning sites is also observed to be uneven, especially when the density of spawners is low. The uppermost reaches of all streams are not freely accessible to spawners and large, anadromous fishes are especially hampered at these levels. As a result of this patchiness at spawning, fry are not uniformly distributed through potential stream habitat when they emerge from the redds. Empirical and experimental evidence indicates that the dispersal of Atlantic salmon fry from sites of emergence is variable, but neither rapid nor extensive (Hay, 1989; Gustafson-Greenwood and Moring, 1990; Beall *et al.*, 1994; Crisp, 1995; Raddum and Fjellheim, 1995). In a Norwegian river, for example, Raddum and Fjellheim (1995) showed dispersal during the first growing season to be as little as 50 m upstream and 175 m downstream from the site of emergence. Gaps in the distribution of redds along spawning streams are often much greater than these distances and, as a result, the uptake of potentially productive stream habitat by young fish must be delayed or incomplete, in some locations at least.

Furthermore, fry suffer density-dependent mortalities (Gee *et al.*, 1978; Egglishaw and Shackley, 1980) and maximum rates of mortality occur during the period in which they disperse (Egglishaw and Shackley, 1977). Mortality rates are expected to be greatest of all when emergence sites are least dispersed and local competition is most intense. More uniform spatial patterns of fry emergence, and lower densities during dispersal,

would be expected to result in greater overall survival through the early stages of stream life.

We therefore propose a new approach to enhancement, based on smoothing the local distribution of progeny derived from natural spawning. Eyed ova recovered in spring (after they become robust to handling) from redds located and marked at spawning time can be redistributed locally within streams. This procedure eliminates hatchery effects. It is also potentially more responsive and more focused than hatchery-based procedures, since redistribution in the spring can be based on assessments of observed patterns of spawning in the preceding autumn. The following trials were carried out to test the effectiveness of excavation as a method for the recovery of ova from naturally spawned redds.

Methods

Redds were located at spawning time (October/ November) in the Newmills Burn, a tributary of the River Don and in the Sheeoch and Girnock Burns which are tributaries of the River Dee. Both rivers are in Aberdeenshire, Scotland. Stream widths at the study locations were in the range 1-3 m.

Redds were detected as apparently discrete areas of gravel disturbance of 0.5 to 2 m in length. The position of redds was recorded photographically or by measurement with reference to fixed points on the stream bank. In addition, a white-painted pebble was pressed into the lowest part of the leading edge of the upstream face of the redd (Figure 1). In most instances, the pebbles remained in position over the winter months, sometimes becoming covered with gravel in-fill. The precision of marking was sufficient to enable the relocation of those pebbles that remained in place to within about 0.2 m. During the period February-April (when previous experience of the same locations indicated that the ova would be eyed and therefore robust to handling), the upstream extremity of each redd was re-located and excavation was carried out.

Excavation was performed by one person or by a team of two, using a horticultural draw hoe to disrupt the stream bed to a depth of 0.2-0.3 m, moving gravel downstream from the redd's up-

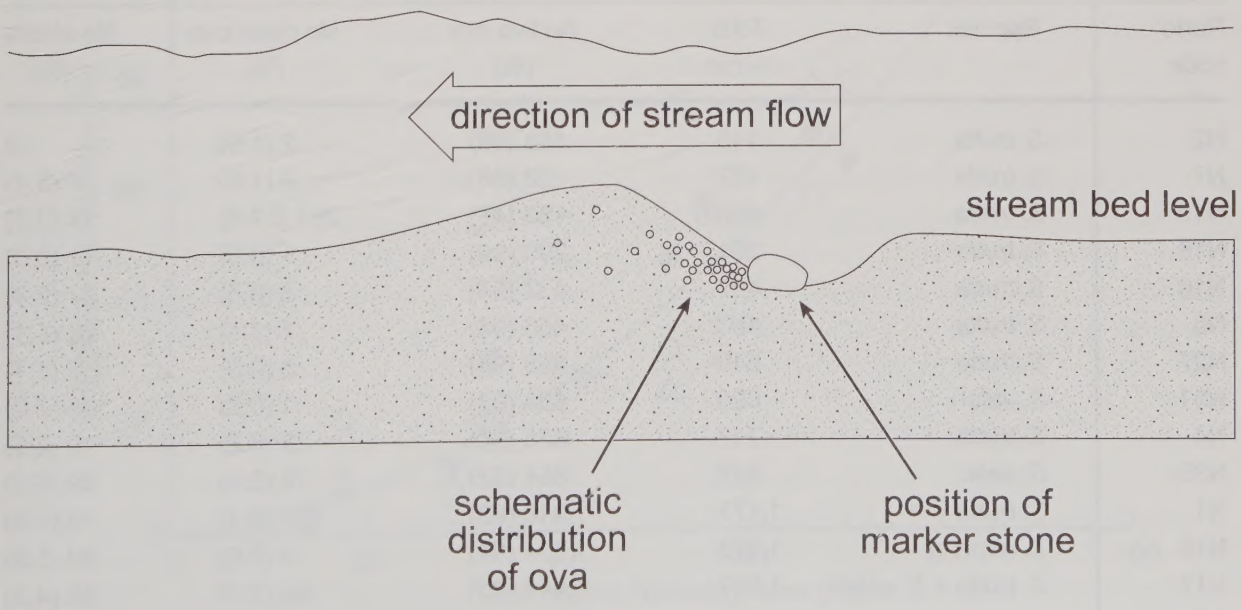

Figure 1. Schematic diagram of the structure of a simple redd unit soon after spawning. The position of a marker stone is indicated.

stream edge. A 600 mm x 400 mm rectangular D-frame net with a 3 mm woven mesh was used to collect disturbed ova from the water column below the excavation site. Excavation was undertaken for separate, timed periods of five minutes until recovery of ova from the redd appeared to be complete or substantially so. For each excavation period, live and dead (opaque) ova were counted separately. Shell cases were also counted and assumed to result from the destruction of ova during excavation.

Samples of live ova (mean n = 249; range = 82-538) from all the Newmills Burn redds were retained on-site in secure perforated plastic containers to determine post-excavation mortalities in the period before hatch. The remainder of the ova were returned to the stream, following the general approach described by Raddum and Fjellheim (1995). After hatch, species was determined in five individuals from each sample group by staining for glucose-phosphate isomerase (GPI) following starch-gel electrophoresis (Vuorinen and Piironen, 1984).

Results

Two of 17 redds excavated were found to be void. Most of the Newmills Burn redds (codes N1-N31) contained only brown trout but N30 and N31 contained only Atlantic salmon. N17 contained a mixture of both salmon and trout (Table 1). Redd G1 (Girnock Burn) was constructed above a fish-trap and was known to have been constructed by salmon. No samples were available for species determination for redd S1 (Sheeoch Burn), but its size and location and the appearance of the ova it contained indicated that it also had been created by salmon.

The total recoverable contents of each redd are given in Table 1. Total recovery (live ova, opaque ova and shells) varied from *ca* 100 to more than 2,000. The incidence of opaque ova varied among redds from 0.3% to 57%. The frequency of shells averaged 3.6% with a maximum value of 7.2%

With the exception of void redds, ova were recovered from every redd within the first five minute period of excavation. On average, 29% of the final recoverable contents were obtained during this period but values ranged from 0.2% to 99%.

Table 1. Species identity and recoverable contents of salmonid redds

Redd code	Species	Total items	No live ova (%)	No dead ova (%)	No shells (%)
N2	*S. trutta*	110	108 (98)	2 (1.8)	0
N7	*S. trutta*	137	128 (93)	2 (1.5)	7 (5.1)
N19	*S. trutta*	458	183 (40)	261 (57.0)	14 (3.1)
N18	*S. trutta*	301	299 (99)	1 (0.3)	1 (0.3)
N16	*S. trutta*	467	437 (94)	3 (0.6)	27 (5.8)
N8	*S. trutta*	483	456 (94)	7 (1.4)	20 (4.1)
N27	*S. trutta*	549	538 (98)	5 (0.9)	6 (1.1)
N31	*S. salar*	629	583 (93)	1 (0.2)	45 (7.2)
N4	*S. trutta*	717	675 (94)	23 (3.2)	19 (2.6)
N30	*S. salar*	932	854 (92)	19 (2.0)	59 (6.3)
N1	*S. trutta*	1,173	1,048 (89)	107 (9.1)	18 (1.5)
N15	*S. trutta*	1,423	1,334 (94)	9 (0.6)	80 (5.6)
N17	*S. trutta* + *S. salar*	1,987	1,844 (93)	60 (3.0)	83 (4.2)
G1		2,200	1,648 (75)	427 (19.4)	125 (5.7)
S1		2,265	2,234 (99)	10 (0.4)	21 (0.9)

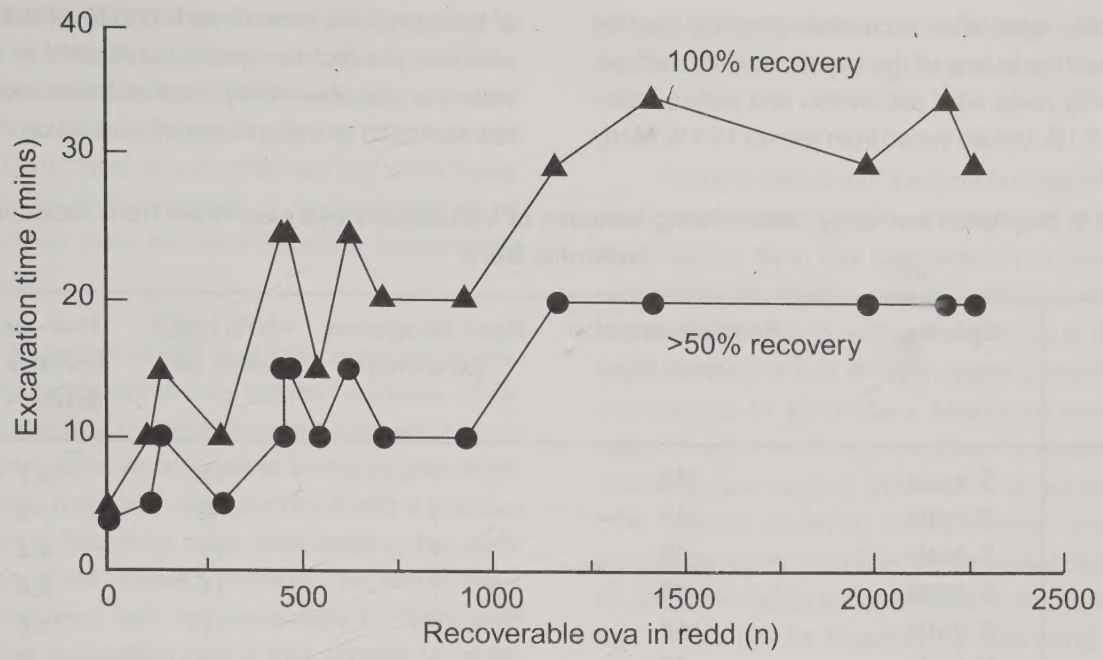

Figure 2. Rates of recovery of ova (live, opaque and shells) from redds. The relationship between the recoverable contents of redds and the cumulative excavation times required for 100% and 50% recovery are indicated.

Figure 2 shows the cumulative excavation times required to exceed 50%, or to accumulate 100%, of the recoverable contents of each redd. For the larger redd locations (>1,000 ova), recovery of more than 50% (average = 64%) of the contents was accomplished in 20 minutes of excavation and recovery was complete after 30-35 minutes. Redds containing fewer ova required lesser periods of excavation to achieve the same levels of recovery.

Figure 3 shows recovery profiles from the five largest redds (>1,000 recoverable ova: 30-35 minutes for total recovery of ova). Rates of recovery tended to be least in the early stages of excavation but essentially constant thereafter until the final stage of the recovery process.

Table 2 shows the week number when each redd was constructed, when it was excavated and when 50% hatch of a sample of ova was exceeded.

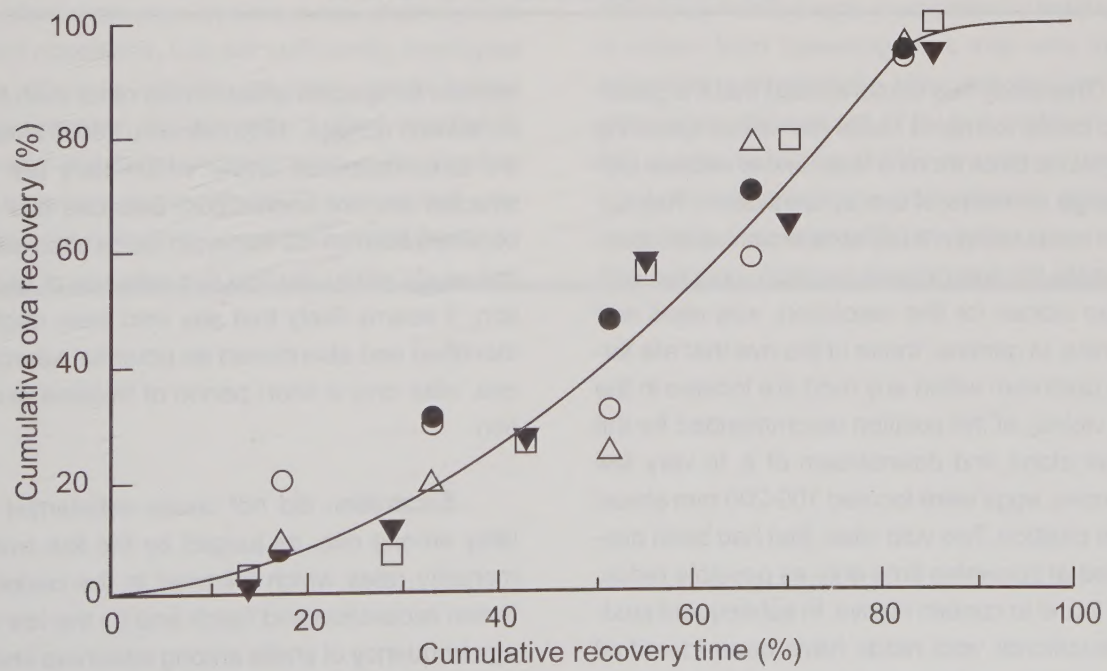

Figure 3. Recovery profiles for excavation of redd contents (live and opaque ova and shells). Cumulative recovery from each of five large redds is denoted by a different symbol.

Mortality rates after excavation bore no marked relationship to any of the key dates. On average, mortality rates after excavation and before hatch were 3.1%. Values varied from zero to 15.7%. Many of the mortalities were observed to be of ova without embryos (but remaining translucent at excavation) or with abnormally small embryos and were not attributed to the process of excavation.

Table 2. Pre-hatch mortality rates among samples of translucent ova excavated from redds in the Newmills Burn

Redd	Species	Redd construction (week no)	Redd excavation (week no)	>50% hatch (week no)	Post- excav mortality rate to hatch (%)
N2	*S. trutta*	45	7	11	**15.7**
N7	*S. trutta*	47	7	9	**0**
N19	*S. trutta*	48	7	11	**4.4**
N18	*S. trutta*	48	7	11	**2.4**
N16	*S. trutta*	48	7	11	**1.8**
N8	*S. trutta*	47	8	11	**0**
N27	*S. trutta*	48	8	11	**0.6**
N31	*S. salar*	48	8	12	**2.3**
N4	*S. trutta*	45	7	9	**1.5**
N30	*S. salar*	48	8	11	**8.0**
N1	*S. trutta*	45	6	9	**1.0**
N15	*S. trutta*	48	7	11	**1.4**
N17	*S. trutta* + *S. salar*	48	7	12	**1.8**

Discussion

This study has demonstrated that it is possible to locate salmonid redds marked at spawning time, two to three months later, and to recover rapidly large numbers of ova by excavation. Relocation of redds using photographs or bankside measurements for approximate location, coupled with marker stones for fine resolution, was rapid and accurate. In general, those of the ova that are farthest upstream within any redd are located in the near vicinity of the position recommended for the marker stone and downstream of it. In very few instances, eggs were located 100-200 mm ahead of this position. Two void sites, that had been designated at spawning time only as possible redds, were found to contain no ova. In subsequent studies, additional void redds have been identified which appeared normal and complete at spawning time. False or void redds have been documented for species of salmonids other than Atlantic salmon (Briggs, 1953; Vernon, 1962) although the circumstances under which they are constructed are not understood. Because ova were obtained from all the non-void redds excavated in this study within the first five minutes of excavation, it seems likely that any void sites might be identified and abandoned as potential sources of ova, after only a short period of fruitless excavation.

Excavation did not cause substantial mortality among ova, as judged by the low average mortality rates which followed in the period between excavation and hatch and by the low average frequency of shells among intact ova immediately after excavation. Salmonid ova are surprisingly resistant to moderate shearing or compres-

sion forces. When they do rupture, they tend to split — usually incompletely — into two equal parts. The net mesh used to gather ova was tested for its efficiency in retaining shells and retention was found to be total, even in relatively fast water flows. Estimates of the number of shells produced by excavation were probably therefore substantially accurate.

Recovery of ova was completed more rapidly for redds containing smaller numbers of recoverable ova. In absolute terms, however, overall recovery rates were greatest for the largest redds reaching maximum values of *ca* 2,000-4,000 ova per hour. Recovery rates were least in the early stages of the recovery process. Thereafter, average recovery rate was essentially constant until the final excavation period that signalled that recovery was substantially complete. No test of the absolute level of recovery of ova could be devised, but the typically curtailed form of the recovery profile suggests that excavation is highly efficient. Although the netting procedure also appeared efficient, some ova were not captured from the water column and lost to the stream.

Rates of recovery of ova were sufficient to indicate that excavation and redistribution is likely to be a viable addition to the range of management techniques available for enhancing salmonid production in streams. The scale on which redistribution might be carried out is limited by available effort more than by time since, under typical stream conditions, ova are sufficiently developed to be robust to handling for many weeks before hatch. However, the intensity of effort required to excavate suggests an application in local rather than extensive management. This constraint may not be unduly limiting, given recent emphasis on local genetic populations as the appropriate scale for enhancement (see eg Busack and Currens, 1995).

A single exercise of the type envisaged here might involve the mapping and marking of redds at spawning time, the identification of potential voids in fry distribution, and the strategic redistribution of eyed ova in spring. The profiles of recovery described in this study suggest a number of approaches to excavation. Maximum absolute rates of ovum recovery are likely to result from directing open-ended allocations of excavation time towards achieving near-complete recovery from large redds. However, when partial recovery of ova from redds is considered more appropriate, this might be targeted by allocating fixed amounts of excavation time to single redds, on the basis of local knowledge regarding the number of ova that they are likely to contain.

Methods for planting out eyed ova in streams are well-developed (see eg Raddum and Fjellheim, 1995). Strategies for redistributing excavated ova might target stream areas above the limit of penetration by spawners, including areas isolated by physical barriers. More generally, redistribution might aim to maximise uptake of fry habitat in reaches of streams where spawning has taken place but where the distribution of redds is patchy or over-spaced. Appropriate intervals for the placement of re-located eggs in potential fry habitat that is distant from spawning sites may vary locally according to stream type. However, studies of the distribution and survival of fry in a northern English stream led Crisp (1995) to suggest that the most effective spacing for point-stocked groups of fry is likely to be about 250 m or less.

Summary

In salmonid enhancement, the conventional countermeasure to the effects of patchiness in the distribution of adults when they spawn is to smooth the distribution of fry throughout potential stream habitat. This is done by returning the progeny of captive-mated spawners to streams via hatcheries. An alternative countermeasure is proposed that is based on natural spawnings and does not require hatchery facilities or specialist skills. Field tests indicate that the redistribution of eyed ova, recovered in spring by excavation of redds located and marked at spawning time, is likely to be feasible, cost-effective and efficient. The approach is also simple and inexpensive and therefore well-suited to the small-scale enhancement of local salmonid populations, using effort based on the interest and involvement of local communities.

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